Document made available under the Patent Cooperation Treaty (PCT)

International application number: PCT/US04/017649

International filing date: 04 June 2004 (04.06.2004)

Document type: Certified copy of priority document

Document details: Country/Office: US
Number: 60/475,673
Filing date: 04 June 2003 (04.06.2003)

Date of receipt at the International Bureau: 19 August 2004 (19.08.2004)

Remark: Priority document submitted or transmitted to the International Bureau in compliance with Rule 17.1(a) or (b)

World Intellectual Property Organization (WIPO) - Geneva, Switzerland
Organisation Mondiale de la Propriété Intellectuelle (OMPI) - Genève, Suisse

1211246

THE UNITED STATES OF AMERICA

TO ALL TO WHOM THESE PRESENTS SHALL COME:

UNITED STATES DEPARTMENT OF COMMERCE

United States Patent and Trademark Office

August 12, 2004

THIS IS TO CERTIFY THAT ANNEXED HERETO IS A TRUE COPY FROM THE RECORDS OF THE UNITED STATES PATENT AND TRADEMARK OFFICE OF THOSE PAPERS OF THE BELOW IDENTIFIED PATENT APPLICATION THAT MET THE REQUIREMENTS TO BE GRANTED A FILING DATE.

APPLICATION NUMBER: ***60/475,673***
FILING DATE: ***June 04, 2003***
RELATED PCT APPLICATION NUMBER: ***PCT/US04/17649***

Certified by

Jon W Dudas

Acting Under Secretary of Commerce
for Intellectual Property
and Acting Director of the U.S.
Patent and Trademark Office

06-05-03

60475673

16075 U.S. PTO

17522 U.S. PTO
60/475673
06/04/03

PTO/SB/16 (10-01)

Approved for use through10/31/2002. OMB 0651-0032
U.S. Patent and Trademark Office; U.S. DEPARTMENT OF COMMERCE

PROVISIONAL APPLICATION FOR PATENT COVER SHEET

This is a request for filing a PROVISIONAL APPLICATION FOR PATENT under 37 CFR 1.53(c).

Express Mail Label No. EV322655958US

INVENTOR(S)

Given Name (first and middle [if any])	Family Name or Surname	Residence (City and either State or Foreign Country)
Feiling	Wang	Medford, Massachusetts

☐ *Additional inventors are being named on the _______ separately numbered sheets attached hereto*

TITLE OF THE INVENTION (500 characters max)

METHOD AND APPARATUS FOR ACQUIRING IMAGES OF OPTICAL INHOMOGENEITY IN SUBSTANCES

Direct all correspondence to: **CORRESPONDENCE ADDRESS**

☐ Customer Number [ ] *Type Customer Number here* → *Place Customer Number Bar Code Label here*

OR

☑ Firm or Individual Name	Mills & Onello LLP				
Address	Eleven Beacon Street				
Address	Suite 605				
City	Boston	State	MA	ZIP	02108
Country	United States	Telephone	(617) 994-4900	Fax	(617) 742-7774

ENCLOSED APPLICATION PARTS ***(check all that apply)***

☑ Specification *Number of Pages* 13

☐ Drawing(s) *Number of Sheets*

☐ Application Data Sheet. See 37 CFR 1.76

☐ CD(s), Number

☐ Other (specify)

METHOD OF PAYMENT OF FILING FEES FOR THIS PROVISIONAL APPLICATION FOR PATENT

☐ Applicant claims small entity status. See 37 CFR 1.27.

☑ A check or money order is enclosed to cover the filing fees

☑ The Commissioner is hereby authorized to charge filing fees or credit any overpayment to Deposit Account Number: 50-1798

☐ Payment by credit card. Form PTO-2038 is attached.

FILING FEE AMOUNT ($): $160.00

The invention was made by an agency of the United States Government or under a contract with an agency of the United States Government.

☑ No.

☐ Yes, the name of the U.S. Government agency and the Government contract number are: ____________

Respectfully submitted,

SIGNATURE [signature]

Date 06/04/2003

TYPED or PRINTED NAME Steven M. Mills

REGISTRATION NO. *(if appropriate)* 36,610

TELEPHONE (617) 994-4901

Docket Number: TOM-0001PR

USE ONLY FOR FILING A PROVISIONAL APPLICATION FOR PATENT

60475673 .060403

PATENT
Attorney Docket No.: TOM-0001PR

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Applicant(s): Feiling Wang
Filing Date: Herewith
Title: METHOD AND APPARATUS FOR ACQUIRING IMAGES OF OPTICAL INHOMOGENEITY IN SUBSTANCES

CERTIFICATE OF MAILING UNDER 37 C.F.R.§ 1.10

"Express Mail" Mailing Label Number EV322655958US I hereby certify that this paper and other papers enclosed herewith or fee is being deposited with the United States Postal Service "Express Mail Post Office to Addressee" service under 37 CFR 1.10 on the date indicated below and is addressed to Mail Stop Provisional Patent Application, Commissioner for Patents, P.O. Box 1450, Alexandria, VA 22313-1450.

June 4, 2003
Date

Christopher Hren

Mail Stop Provisional Patent Application
Commissioner for Patents
P.O. Box 1450
Alexandria, VA 22313-1450

Sir:

TRANSMITTAL LETTER

Enclosed herewith for filing in the above-identified provisional patent application please find the following listed items:

1. Provisional Application Cover Sheet;
2. Provisional Patent Application including thirteen (13) pages of specification;
3. Check in the amount of $160.00 to cover application filing fee; and
4. Return Postcard.

In connection with the foregoing matter, please charge any additional fees which may be due, or credit any overpayment, to Deposit Account Number 50-1798. A duplicate copy of this letter is provided for this purpose.

Respectfully submitted,

Date: June 4, 2003

Mills & Onello LLP
Eleven Beacon Street, Suite 605
Boston, MA 02108
Telephone: (617) 994-4900
Facsimile: (617) 742-7774

Steven M. Mills
Registration Number 36,610
Attorney for Applicant

J:\TOM\0001PR\transprovisionalapp.wpd

Invention Disclosure

Title: Method and Apparatus for Acquiring Images of Optical Inhomogeneity in Substances.

Inventor: Feiling Wang

Address: 54 Forest St. Unit 322, Medford, MA 02155

Phone: 781-393-8518, Facsimile: 781-393-8517

Description of Invention

The invented method and apparatus are for the purpose of acquiring, by means of a nondestructive process, images which reveal optical inhomogeneity in a volume of substances.

The invented apparatus embodies the physical principle of range detection by means of the interference of low-coherence light and optical phase detection by means of a phase modulation scheme. A possible implementation of the system is shown in Fig. 1.

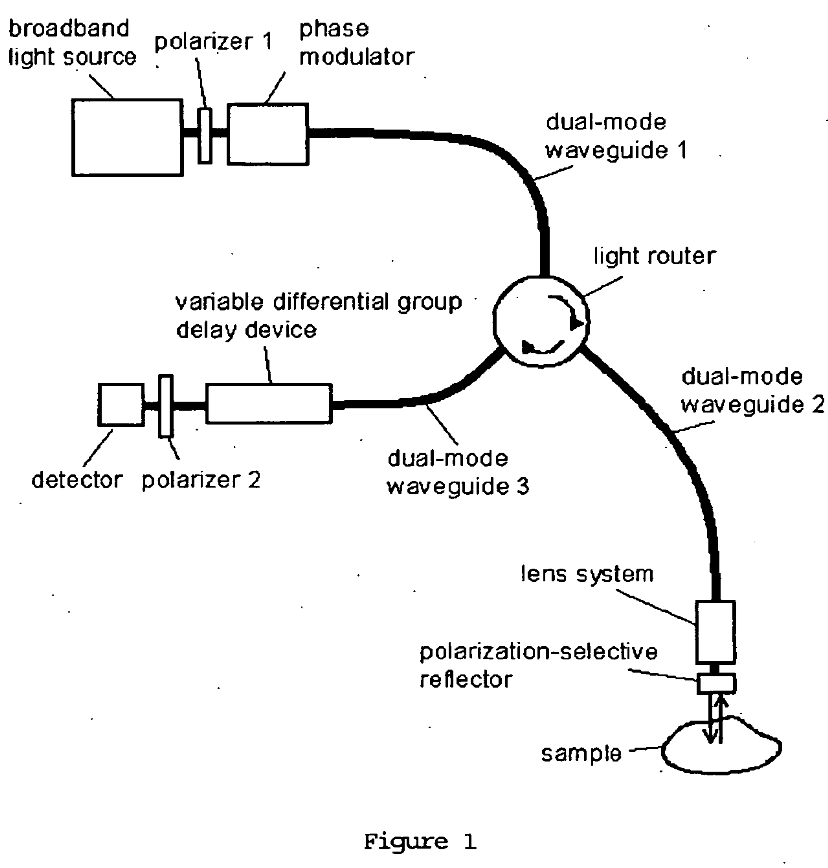

Figure 1

Light radiation from the Broadband Light Source (Source) is transmitted through Polarizer 1 that is oriented to allow the light to form both of the guided propagation modes in Dual-mode Waveguide 1 (Waveguide 1). The Optical Phase Modulator (Modulator) is employed to modulate the optical phase of light in one guided mode relative to the other. The Light Router (Router) directs light waves from Waveguide 1 to Dual-mode Waveguide 2 (Waveguide 2). At the end of Waveguide 2, the Lens System collimates or focuses the light beams. One of the two guided waves is reflected back to Waveguide 2 by the Polarization-selective Reflector (PSR) while the other mode is transmitted to impinge on the sample. Back reflected or scattered the light from the sample is collected by the Lens System to propagate towards the Router along with the light reflected by PSR. The Router directs the light waves traveling towards it in Waveguide 2 to Dual-mode Waveguide 3 (Waveguide 3). A Variable Differential Group Delay (VDGD) device is inserted in or connected to Waveguide 3. The function of the VDGD is to introduce a controllable amount of optical path difference between the two waves. Placed in front of the Detector, Polarizer 2 projects both of the guided waves onto the same polarization direction so that the changes in optical path difference and the optical phase difference between the two propagation modes cause intensity variations, detectable by the Detector.

The spectrum of the Source must be broad enough in order for the system to have sufficient ranging resolution. Some semiconductor light emitting diodes (LED) and amplified spontaneous emission (ASE) sources possess the appropriate spectral properties for the purpose. The Modulator must be the variable waveplate type. In other words, the modulator should vary the optical phase in one guided wave with respect to the other. Electro-optic materials such as $LiNbO_3$ crystal and PLZT ceramic can be used to construct this kind of modulators. The dual-mode waveguides (Waveguide 1 to 3) must be able to support two distinctive propagation modes which are mutually orthogonal to one another. One kind of practical and commercially available waveguide is the polarization maintaining optical fiber. A polarization maintaining fiber can carry two propagation modes, namely, the s-wave polarized along its slow axis and the p-wave polarized along its fast axis. In good quality polarization maintaining fibers these two modes have virtually no energy exchange, or coupling. The Router directs the flow of optical waves according to the following scheme: incoming light waves from Waveguide 1 are routed to Waveguide 2; incoming light waves from Waveguide 2 are routed to Waveguide 3. The Router is ideally required to maintain the separation of the guided modes. For instance, the s-wave in Waveguide 1 should be routed to Waveguide 2 as s-wave or p-wave only. In

practice, one can use a polarization-maintaining circulator in which there is minimal mode coupling. The lens system is used to concentrate the light energy into a small area, facilitating spatially resolved studies of the sample in a lateral direction. The Polarization-selective Reflector (PSR) is to reverse the propagation direction of one of the two waves in Waveguide 2 as it reaches the end of the waveguide while transmitting the orthogonal wave. The PSR may consists of a polarization sensitive beam splitter and a mirror as shown in Fig. 2. In the assembly the polarizing beam splitter reflects one of the two waves, s-wave shown, while transmitting the other. The mirror, that can be directly coated on the beam splitter, reflects the light that subsequently bounces from the splitter the second time before re-entering the waveguide through the Lens System.

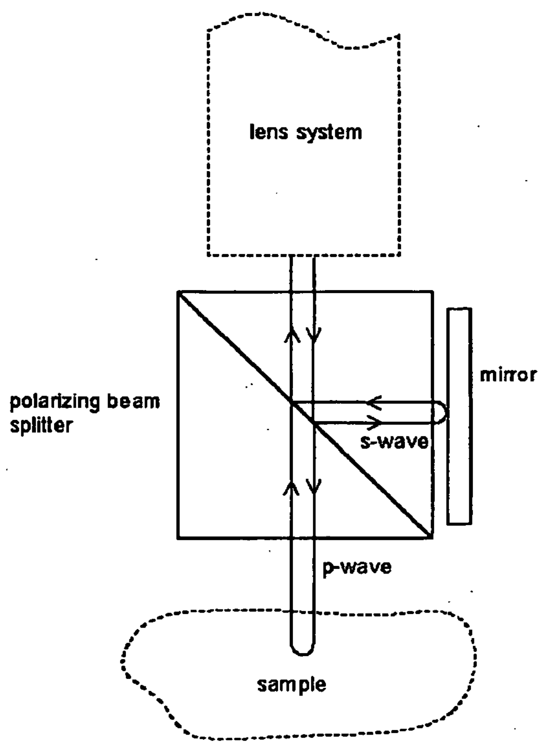

Figure 2

A number of hardware choices are available for the VDGD device. For instance, an assembly of a polarizing beam splitter(s) and a movable collimator or mirror, that provides the adjustable path length for one of the two waves, can be used. Another possible choice is a piezoelectric stretcher of polarization maintaining fibers.

Using the above-mentioned interferometer to acquire images of optical inhomogeneity in samples data acquisition and control electronics must be added. A design diagram for such a system is shown in Fig. 3.

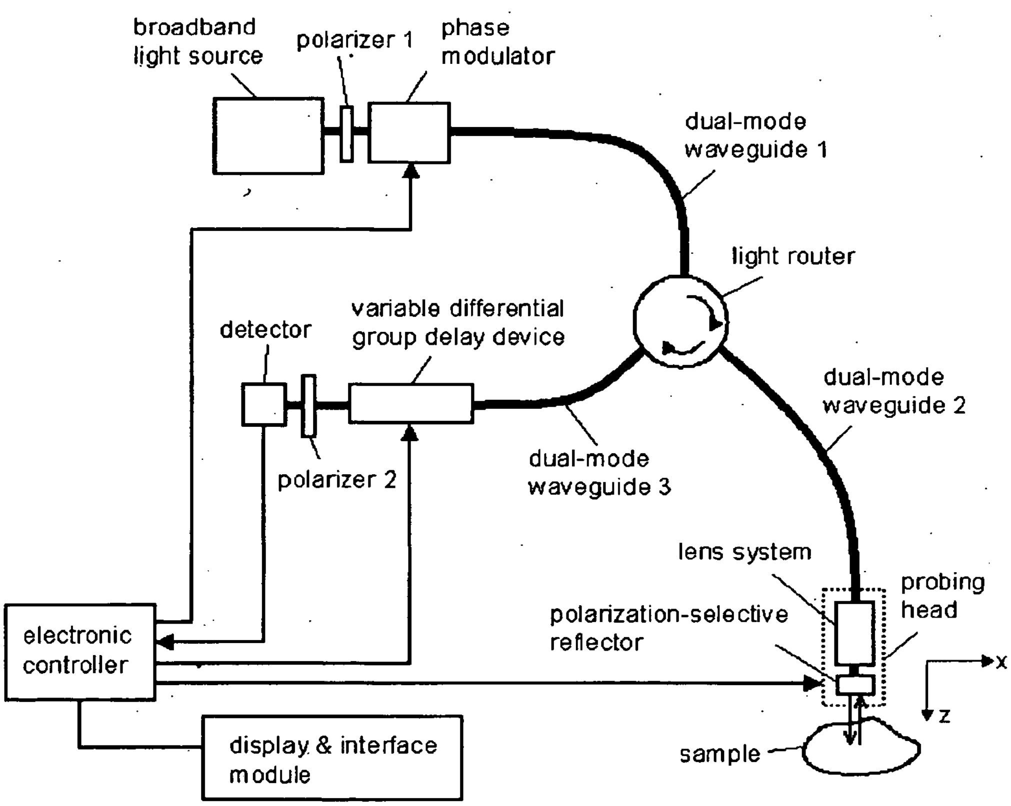

Figure 3

The electronic controller, according to the instructions from the human interface, executes an appropriate program that includes delivering driving signals to Modulator, VDGD and the moving mechanisms of Probing Head, taking and storing photo-electric signal from the detector, processing the stored information, sending signals and data to be displayed on Display Module. A preferred mode of operation is described below.

The light from the Source is typically partially polarized. It is preferable to align Polarizer 1 so that maximum amount of light is transmitted and that the transmitted light is coupled to both of the guided modes in Waveguide 1 with the same amplitude. If we designate the electric field transmitting the polarizer E, the electric fields in Waveguide 1 in the two guided modes can be expressed as:

$$\begin{cases} E_s = \dfrac{1}{\sqrt{2}} E, \\ E_p = \dfrac{1}{\sqrt{2}} E. \end{cases} \tag{1}$$

It should be appreciated that the light has a finite spectral width (broadband or partially coherent). The fields can be described by the following Fourier integral:

$$E = \int E_\omega e^{j\omega t} d\omega \ . \tag{2}$$

For the simplicity of the analysis, let us first consider a thin slice of the spectrum, i.e. a lightwave of a specific wavelength. Without loosing generality we can assume all the components, including polarizers, waveguides, Router, PSR and VDGD, are lossless. Let us designate the reflection coefficient of the sample r, that is complex in nature. The p-wave picks up an optical phase, Γ, relative to the s-wave as they reach Polarizer 2:

$$\begin{cases} E_s = \dfrac{1}{\sqrt{2}} E, \\ E_p = \dfrac{1}{\sqrt{2}} rE\, e^{j\Gamma}. \end{cases} \tag{3}$$

The light that passes through Polarizer 2 can be expressed by

$$E_a = \frac{1}{\sqrt{2}}(E_s + E_p) = \frac{1}{2} E\left(1 + r e^{j\Gamma}\right). \tag{4}$$

The intensity of the light that impinges on the photo-detector is given by:

$$I = E_a E_a^* = \frac{1}{4}|E|^2\left[1 + |r|^2 + 2|r|\cos(\Gamma + \delta)\right]. \tag{5}$$

where phase angle δ reflects the complex nature of the reflection coefficient of the sample and is defined by

$$r = |r| e^{j\delta} . \tag{6}$$

Now if we let Modulator to exert a sinusoidal phase modulation, with magnitude M and frequency Ω, in the p-wave with respect to the s-wave, we can rewrite the light intensity as follows:

$$I = \frac{1+|r|^2}{4}|E|^2 + \frac{|r|}{2}|E|^2 \cos[M\sin(\Omega t) + \varphi + \delta] \quad . \tag{7}$$

where phase angle φ is the accumulated phase slip between the two modes, not including the periodic modulation due to Modulator. We can adjust the system, by means of the VDGD or the static phase shift in Modulator, to eliminate φ. The waveform of I is graphically shown in Fig. 4.

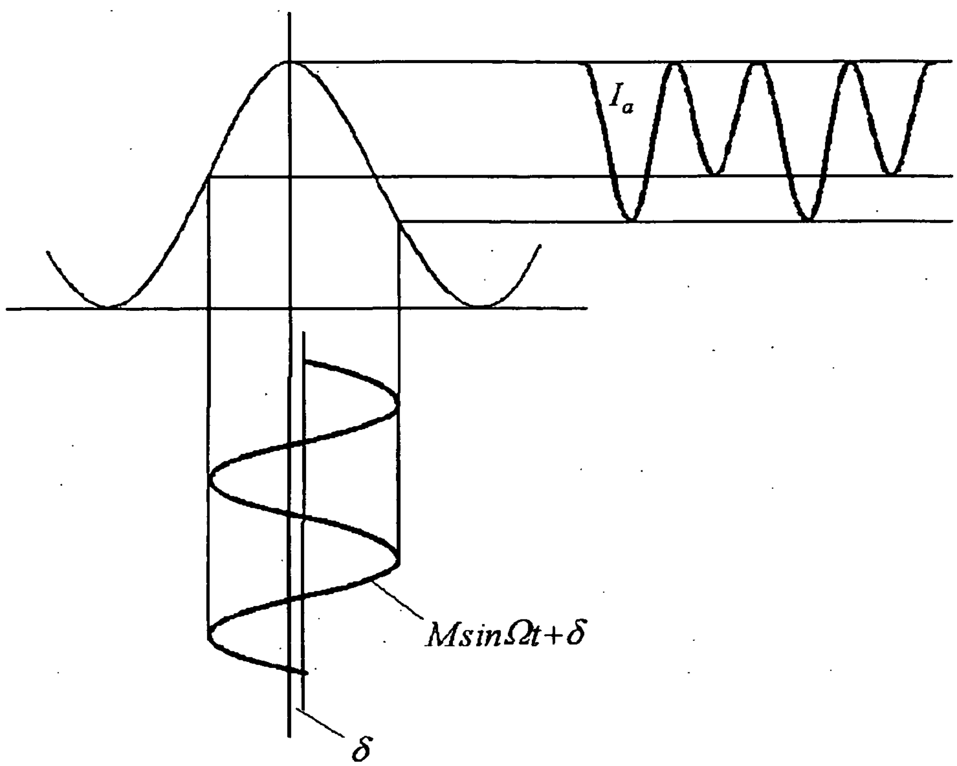

Figure 4

From the figure we can see that the detected light intensity exhibits an oscillating waveform that possesses a base frequency of Ω and its harmonics. The amplitudes of the base frequency and each of the harmonics are related to δ and $|r|$. It is straightforward to derive the mathematical expressions for the

relationships between r and the harmonics. For instance, the amplitude of the base-frequency oscillation and the second harmonic are found to be:

$$A_{\Omega} = 0.5|E|^2 J_1(M)|r|\sin\delta \;; \tag{8a}$$

$$A_{2\Omega} = 0.5|E|^2 J_2(M)|r|\cos\delta \;, \tag{8b}$$

where J_1 and J_2 are Bessel functions of the first and second order, respectively. From Eq. (8a) and (8b) one can solve for $|r|$ and δ, i.e. the complete characterization of r. We can therefore completely characterize the complex reflection coefficient r by analyzing the harmonic content of various orders in the intensity waveform I. In particular, the presence of the base-frequency component in I is due to a finite δ.

Now let us examine the consequence of having a broadband light source. When there is a significant differential group delay between the two propagation modes there must be an associated large phase slippage φ that is wavelength dependent. A substantial wavelength spread in the light source means that the phase slippage also possesses a substantial spread. Such a phase spread cannot be eliminated by a phase control device that does not also eliminate the differential group delay. In this case the detected light intensity is given by the following integral:

$$I = \int\left\{\frac{1+|r|^2}{4}|E(\lambda)|^2 + \frac{|r|}{2}|E(\lambda)|^2\cos[M\sin(\Omega t)+\varphi(\lambda)+\delta]\right\}d\lambda \;. \tag{9}$$

It is easy to see that if the range of $\varphi(\lambda)$ is comparable to π for the bandwidth of the light source no oscillation in I can be observed as oscillations for different wavelengths cancel out because of their phase difference. This phenomenon is in close analogy to the interference of white light wherein color fringes are visible only when the path difference is small (the film is thin).

The above analysis demonstrates that the use of a broadband light source enables range detection using the proposed apparatus. In order to do so, we must let the s-wave to have a longer optical path in the system compared to the p-wave (not including its round-trip between Probing Head and Sample). For any given path length difference in the system there must be a matching distance between Probing Head and Sample, z, that cancels out the path length difference. If an oscillation in I is observed the p-wave must be reflected from this specific distance z. By varying the path length difference in the system and record the oscillation waveforms we can therefore acquire the reflection coefficient r as a function of

the longitudinal distance z, or depth. By moving Probing Head laterally, we can also record the variation of r in the lateral directions.

In summary, the described system can be used to acquire information regarding the optical inhomogeneity in a substance by measuring the oscillations in the detected light as a function of the lateral and longitudinal directions. The waveforms can then be used to construct the spatially resolved complex reflection coefficient of the substance under study.

The operation of the described system for acquiring images of optical inhomogeneity should include routines such as the one shown below:

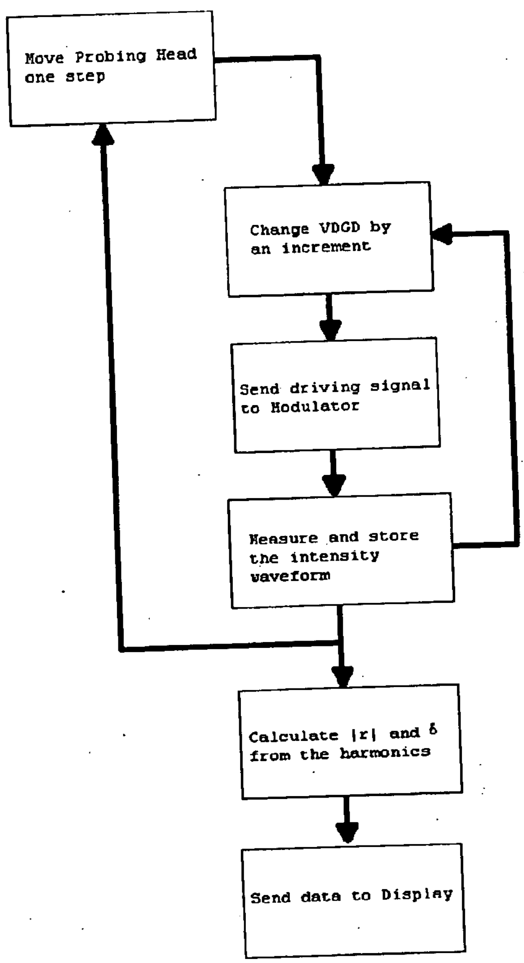

Figure 5

The above shown operation sequence allows us to display and store images of $|r|$ and δ as functions of the lateral and longitudinal directions. The data can be further used to determine the spatial distribution of the refractive index and the absorption coefficient of the substance under study. Images of this kind should be of value to biomedical field for tissue examination and to the study of other layered structures such as oil paintings.

Other Embodiments

Alternative to the optical design shown in Figure 1, there are other possible embodiments of the invention. One such embodiment is shown in Figure 6. In this design, the probing light is delivered to the sample through one dual-mode waveguide and the reflected/scattered light is collected by another dual-mode waveguide. Shown in the figure, Waveguide 1 delivers the light waves to the fiber tip. One of the two modes is reflected into Waveguide 2 while the orthogonal component impinges on the sample. The collection of the reflected/scattered light from the sample is through Waveguide 2. With this probing head, the mirror (shown in Fig. 2) should be aligned so that the light is reflected into Waveguide 2 instead of Waveguide 1. The advantage of this design is the elimination of the optical circulator.

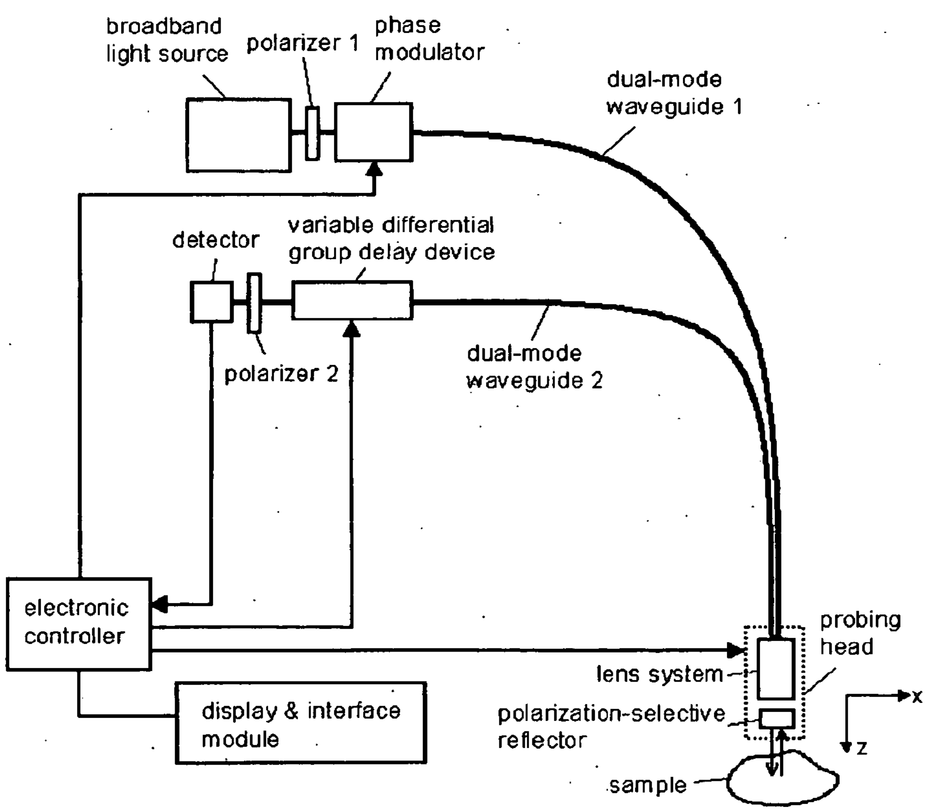

Figure 6

Yet another different embodiment of the invention is shown in Figure 7 in which the design of the probing head is different from what is shown in Figure 1. In place of the polarization-selective reflector, a polarization rotating device is utilized. Details of the probing head is shown in Figure 8.

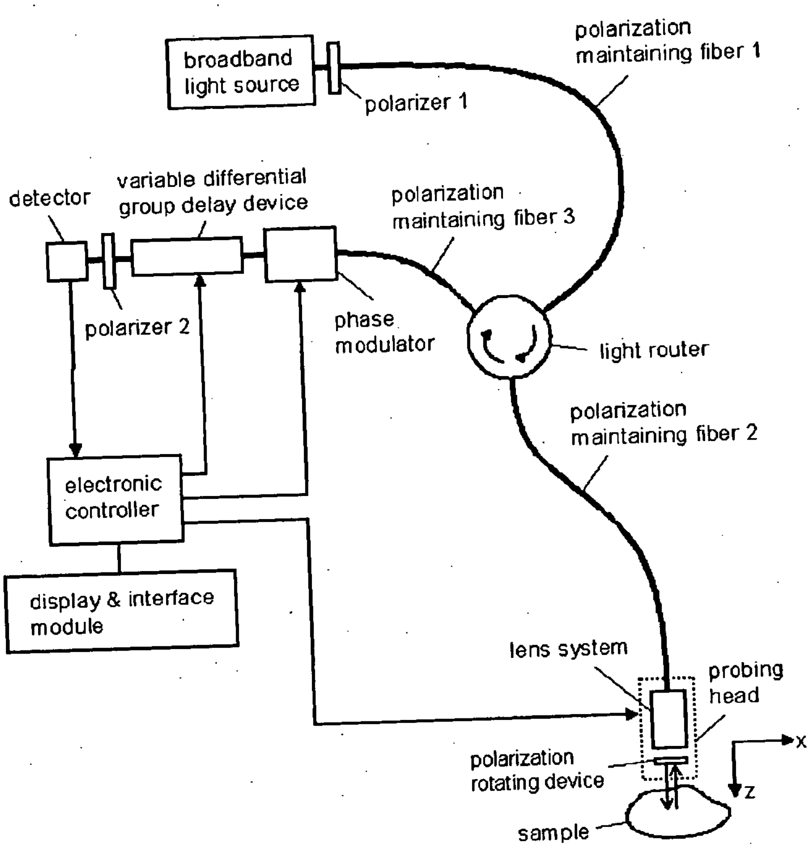

Figure 7

The effect of the polarization rotating device is to convert the state of polarization of the light returning from the sample to the orthogonally linear state. With this probing head design, the light is couple into Polarization Maintaining Fiber 1 (PM Fiber 1) in only one of the two modes, for instance, the polarization mode aligned with the slow axis of the fiber, designated as s-state. The partially reflective surface of the fiber tip causes a portion of the light to

reverse its propagation direction, remaining polarized in the s-state. The other portion of the light exits the fiber and encounters the Quarter-Wave Plate. If the Quarter-Wave Plate is oriented in such a way that its optical axis makes an 45-degree angle with the p-state, the light becomes circularly polarized as it reaches the sample. If the sample is not depolarizing or birefringent the reflected/scattered light remains circularly polarized. Before returning to the fiber, the reflected/scattered light encounters the Quarter-Wave Plate for the second time. Once again the Quarter Wave Plate alters the state of polarization of the probing light, making it linear; however, orthogonal to the s-state. Now there are two modes of light propagating in the reverse direction, i.e., light in s-state reflected by the fiber tip and light in p-state reflected from the sample.

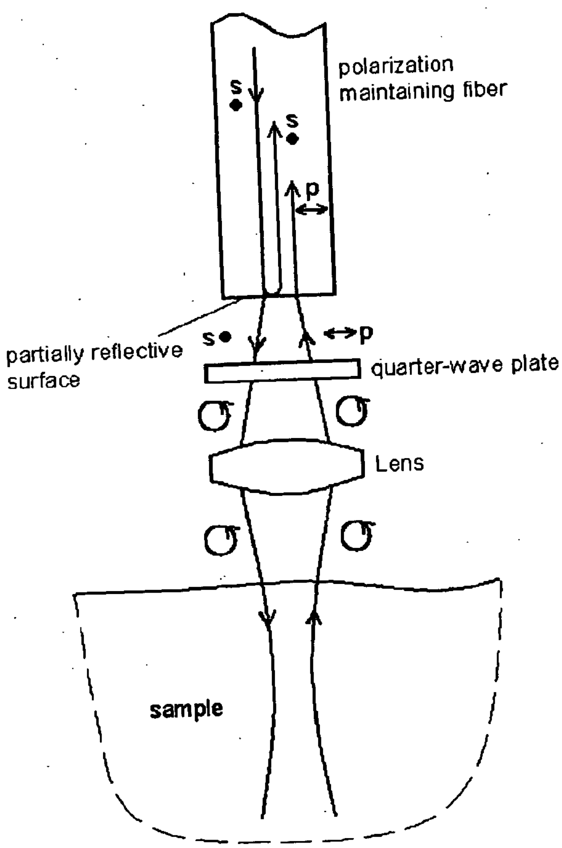

Figure 8

[redacted]

The light in the p-state (from the sample) lags the s-state light because of the extra travel from fiber tip to the sample and returning. As in the first embodiment, the Variable Differential Group Delay (VDGD) device is utilized to equalize the optical path of the two modes for ranging. The Modulator is relocated to Polarization Maintaining Fiber 2 (PM Fiber 2). The effect of the modulator is the same as described earlier, i.e., to create a periodic phase difference between the two modes so that intensity oscillation in a desired fashion is generated.

In all the above-mentioned embodiments there is a common and important feature - both the probing light and reference light travel in the same waveguides except for the extra distance traveled by the probing light between the probing head and the sample. This feature stabilizes the relative phase, or differential optical path, between the probing light and the reference light, even in the presence of mechanical movement of the fibers. This is in contrast to conventional fiber interferometers in which probing light and reference light travel in different branches of fiber, prone to noise caused by the variation in the differential optical path. The stability of the differential optical path, achieved in the invented system, is essential for the determination of the phase angle, δ.

J:\TOM\0001PR\provpatapp.doc